

IoT-Based Solar Panel Cleaning Robot with AI-Assisted Predictive Maintenance and Automatic Reminder System

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Abstract: Solar panels gradually lose efficiency when dust, bird droppings, and environmental debris accumulate on the surface. Manual cleaning is costly, time-consuming, and difficult to apply consistently across large or elevated installations. This paper presents an IoT-based solar panel cleaning robot that combines a water sprinkling mechanism, a motor-driven rotational mop, and an ESP32-WROOM controller with cloud connectivity. The system collects operating data from sensors, transmits the readings to a web-enabled platform, and uses an AI-assisted decision layer to estimate when cleaning is needed. When the panel efficiency falls below the chosen threshold, the user receives an automatic reminder through a web dashboard and can monitor the cleaning status in real time. The proposed architecture supports condition-based maintenance instead of fixed-interval cleaning, with the aim of improving photovoltaic output, reducing water usage, and lowering maintenance overhead.

Keywords : Solar panel cleaning robot, IoT, ESP32-WROOM, predictive maintenance, dust detection, web dashboard, automated cleaning

I. INTRODUCTION

Solar photovoltaic systems have become an important source of renewable electricity, but their output is highly sensitive to surface contamination. Dust, mud, pollen, and bird droppings block incident light and reduce the useful energy captured by the panel. The problem is more pronounced in outdoor systems that are installed on rooftops, in industrial yards, or in remote solar farms, where regular manual inspection is inconvenient. In practice, many installations are cleaned either manually or on a fixed schedule, even though soiling is not constant and the cleaning requirement changes with weather and location.

To address this challenge, the proposed system combines sensing, communication, decision-making, and mechanical cleaning into a single integrated platform. The ESP32-WROOM microcontroller acts as the central controller for motor drivers, relay-based water control, and sensor acquisition. Sensor readings and cleaning status are uploaded to a cloud server through built-in Wi-Fi, where the data can be viewed from a web dashboard. An AI-assisted layer analyzes power output trends and environmental

conditions to estimate the optimal time for cleaning. When cleaning is required, the user is notified and the robotic mechanism performs the cleaning action using a sponge-based rotating mop with controlled water sprinkling.

II. RELATED WORK

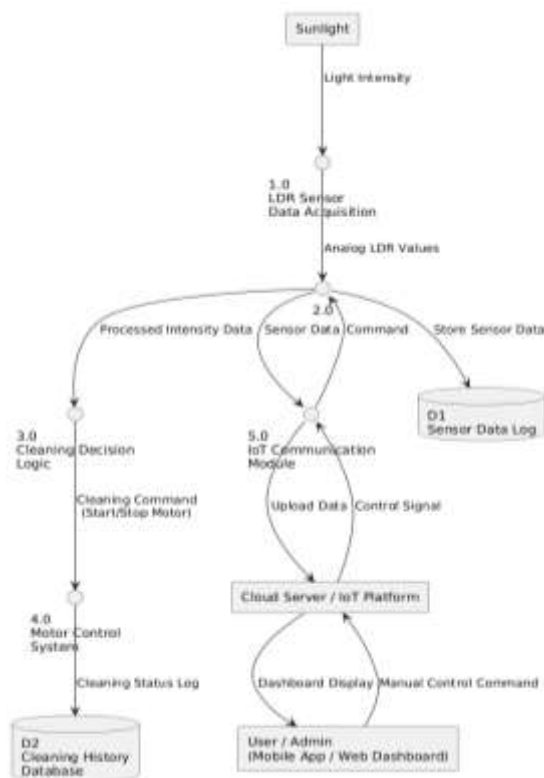
1. **Sayyah et al. (2014):** reported that dust deposition can cause substantial energy loss in photovoltaic panels, establishing the need for frequent maintenance.
2. **Mani and Pillai (2010):** studied the impact of dust on PV performance and highlighted the performance gap created by surface soiling.
3. **IEEE-based automatic cleaning studies (2017):** showed that automated cleaning improves output, but many systems still rely on fixed schedules.
4. **Bansal et al. (2018):** presented robotic cleaning concepts that reduce human effort, though they did not integrate efficiency-aware monitoring.
5. **Lee et al. (2019) and Kumar et al. (2020):** demonstrated IoT-based solar monitoring and remote dashboards, but without physical cleaning action.
6. **Machine-learning studies (2021-2024):** indicated that predictive models can estimate efficiency degradation and improve maintenance timing.

III. PROBLEM STATEMENT

Solar panels suffer efficiency loss due to dust accumulation and environmental contamination. Existing approaches either clean panels at fixed intervals or only monitor panel performance without taking corrective action. Manual inspection and cleaning are inefficient for large solar arrays and rooftop installations. A practical solution is therefore required that can detect performance degradation, decide when cleaning is necessary, notify the user, and execute the cleaning process with minimal human intervention.

IV. SYSTEM OVERVIEW

The proposed architecture is organized into three coordinated layers: the sensing layer, the IoT and decision layer, and the cleaning layer. The sensing layer collects light intensity and operational data using the LDR sensor and other panel-related inputs. The IoT and decision layer processes the sensor values, communicates with the cloud platform, and updates the cleaning recommendation. The cleaning layer drives the motors, water pump, and sponge mechanism to remove dust from the panel surface. Cleaning history is stored in a database, while the dashboard provides a visible record of sensor data, control actions, and maintenance events.



IOT-Based Solar Panel Cleaning Robot - Data Flow Diagram (Leval)

1. External Entity: Sunlight

- The system begins with sunlight, which acts as an external data source.
- It provides light intensity, which is a key environmental parameter affecting solar panel efficiency.

2. Process 1.0 – LDR Sensor Data Acquisition

- This process represents data acquisition from the physical environment.
- An LDR (Light Dependent Resistor) senses light intensity and converts it into analog electrical signals.
- The output is raw sensor data, which cannot yet be used directly for decision-making.

3. Process 2.0 – Sensor Data Processing

- This is a data transformation stage.
- It:
 - Converts analog signals into interpretable digital values.
 - Structures the data into a usable format (e.g., intensity levels).
- The processed data is then:
 - Stored in D1: Sensor Data Log (data persistence).
 - Sent to Cleaning Logic (3.0) for decision-making.
 - Shared with the IoT Communication Module (5.0).

4. Data Store D1 – Sensor Data Log

- Acts as a repository for historical sensor readings.
- Supports:
 - Trend analysis
 - System monitoring
 - Future optimization

5. Process 3.0 – Cleaning Decision Logic

- This is the core decision-making unit.
- It applies predefined rules or algorithms (threshold-based logic) to determine:
 - Whether the panel is dirty (e.g., reduced light intensity).
- Produces a control output:
 - Cleaning command (Start/Stop motor)

6. Process 4.0 – Motor Control System

- Represents the actuation layer of the system.
- Converts logical commands into physical actions:
 - Activates motors to clean the panel surface.
- Generates operational feedback stored in: D2:
 - Cleaning History Database

7. Data Store D2 – Cleaning History Database

- Maintains records of:
 - Cleaning operations
 - Time, duration, and frequency
- Useful for:
 - Performance evaluation
 - Maintenance scheduling

8. Process 5.0 – IoT Communication Module

- Functions as a communication interface between the robot and external systems.
- Responsibilities include:
 - Uploading sensor and system data to the cloud.
 - Receiving remote control commands.
- Enables bidirectional data flow.

9. Cloud Server / IoT Platform

- Acts as a centralized processing and storage system.
- Performs:
 - Data aggregation
 - Remote monitoring
 - Command generation
- Serves as an intermediary between the robot and users.

10. External Entity: User/Admin

- Represents human interaction with the system.
- Accesses data through:
 - Mobile applications or web dashboards
- Can:
 - Monitor system status (dashboard display)
 - Send manual override commands

1. Core Controller: ESP32-WROOM (38 pin) microcontroller

- At the center is the ESP32-WROOM (38 pin), which acts as the “brain” of the system.
- Sends control signals to motor drivers and relay.
- Likely programmed to move the robot across the panel and activate cleaning.

2. L298N Dual H-Bridge Motor Driver

- Controls four DC motors (M1–M4)
- Works as two H-bridges:
 - One H-bridge → Motors M1 & M2
 - Other H-bridge → Motors M3 & M4
- Pins:
 - IN1–IN4 → Direction control (from ESP32)
 - ENA, ENB → Speed control (PWM)
 - OUT1–OUT4 → Connected to motors

3. Motors (M1–M4)

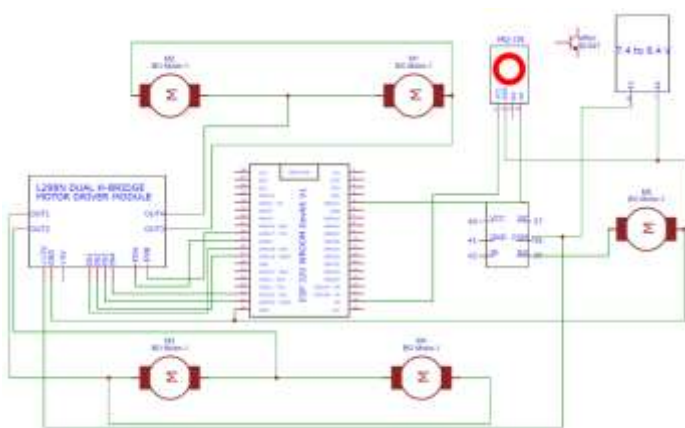
- BO motors (gear motors) used for locomotion.
- Likely arranged as:
 - Two motors per side (left & right wheels).
- Enable:
 - Forward/backward motion
 - Turning (by varying speed/direction of each side)

4. Power Supply

- Battery: 7.4V–8.4V (likely 2× Li-ion cells)
- Powers:
 - L298N (motor supply)
 - Cleaning motor (via relay)
- ESP32 may be powered via regulated 5V or onboard regulator.

5. Cleaning Mechanism

- Motor M5
 - Drives brush / wiper / water pump.
- Control Circuit:
 - BC547 Transistor : Acts as a switch controlled by ESP32.
- Relay Module
 - Pins:



V. CIRCUIT DIAGRAM

This Circuit diagram shows a “solar panel cleaning robot” built around an ESP32 (38 pin WROOM) microcontroller, using multiple DC motors for movement and a relay/transistor setup for an additional cleaning mechanism (like a brush or pump).

- VCC, GND → Power
- IN → Control signal from ESP32
- COM, NO → Switch contacts

6. Dust Sensor (MQ-135)

- The module labeled MQ-135 is an air quality/dust sensor : MQ_135 Gas Sensor
- Pins:

- VCC/GND - Power
- A0 - Analog Output
- D0 - Digital Threshold output

- Function :

- Detects pollution/ dust level near the panel
- ESP32 decides whether cleaning is needed

1. ESP32 controls wheel motors via L298N → robot moves over solar panel.
2. When cleaning is needed:

- Relay is triggered.
- Cleaning motor (M5) runs → rotates brush or sprays water.

3. Robot likely follows a programmed path to clean the panel surface.

Observation

- L298N is simple but inefficient (voltage drop ~2V).
- All motors share battery → ensure sufficient current capacity.
- Relay + transistor ensures safe switching of cleaning motor.
- Air Quality Sensor MQ135 : To Sense the following parameters
- Target Gases: Ammonia (NH₃), Nitrogen Oxides (NO_x), Alcohol, Benzene, Smoke, and CO₂.
- Pre-heating: Requires a 24-hour "burn-in" for the first use and 2–5 minutes of pre-heating every time it is powered on for stable readings.

Component	ESP32 Pin	Pin Function	Note
MQ135 (VCC)	VIN/5V	Power	Connect to 5V for the internal heater
MQ135 (Analog Out)	GPIO 34	ADC_CH6	Measures gas connection
LDR (Signal)	GPIO 35	ADC_CH7	Part of a 10kΩ Voltage Divider
L298N (IN1)	GPIO 12	Digital Out	Motor A Forward
L298N (IN2)	GPIO 13	Digital Out	Motor A Backward
L298N (IN3)	GPIO 14	Digital Out	Motor B Forward
L298N (IN4)	GPIO 27	Digital Out	Motor B Backward
Cleaning Brush	GPIO 26	Digital Out	Relay or Transistor trigger

VI. METHODOLOGY

The methodology begins with hardware integration and continues through embedded control, cloud communication, data preprocessing, predictive cleaning, and dashboard visualization. The ESP32 executes the control logic for the cleaning robot, while the motor driver and relay module manage the motion system and water sprayer. Sensor values are sampled and transmitted to the cloud in structured form. Historical readings and cleaning records are then used to support the predictive layer, which estimates whether the panel requires cleaning.

5.1 Hardware, Software and Embedded Control

The hardware platform uses the ESP32-WROOM (38-pin) microcontroller, DC geared motors, a motor driver module, a water pump, an LDR module, a relay, a power supply, and the sponge-based mop assembly. The microcontroller handles PWM motor control, relay switching, and sensor data acquisition. The low-voltage regulator and power conditioning section provide stable supply to the control electronics.

1. Hardware Components

The hardware architecture of the proposed “Solar Panel Cleaner Robot” is designed to improve the photovoltaic efficiency of solar panels by removing dust and debris while simultaneously acting as a mobile environmental monitoring station.

A. The Controller: ESP32-WROOM (38-Pin)

The 38-pin variant provides more accessible Ground and Power pins than the 30-pin version. Operating Voltage: 3.3VADC Resolution: 12-bit (0-4095). Important Note: We will use ADC1 pins (GPIO 32-39) because ADC2 cannot be used when Wi-Fi is active.

B. Air Quality Sensor: MQ135

- Target Gases: Ammonia (NH₃), Nitrogen Oxides (NO_x), Alcohol, Benzene, Smoke, and CO₂.
- Pre-heating: Requires a 24-hour "burn-in" for the first use and 2–5 minutes of pre-heating every time it is powered on for stable readings

C. Light Sensor: LDR (Photoresistor)

Measures ambient light to ensure the robot only operates during daylight and returns to a "home" position or sleep mode at night.

D. L298N Motor Driver Module

The L298N motor driver module is a high-power, dual-channel H-Bridge controller designed to control the speed and direction of up to two DC motors or one stepper motor.

It acts as an interface between a microcontroller (like Arduino) and motors, handling high currents (up to 2A per channel) and voltages (5V to 35V) that microcontrollers cannot supply directly.

E. LM2596S Power Supply

DC-DC Buck Converter Step Down Module LM2596 Power Supply is a step-down(buck) switching regulator, capable of driving a 3-A load with excellent line and load regulation. These devices are available in fixed output voltages of 3.3 V, 5 V, 12 V, and an adjustable output version.

F. Relay

The SRD-05VDC-SL-C is a 5V DC relay module manufactured by SONGLE. It is designed to enable low voltage control signals to switch high voltage devices, making it an essential component in automation, home appliances, and IoT projects.

G. Lithium ion Battery

Lithium-ion (Li-ion) batteries are the dominant rechargeable technology for portable electronics and electric vehicles due to their high energy density, lightweight nature, and long cycle life. They operate by moving lithium ions between cathode and anode electrodes, usually paired with a, [!embed] carbon-based anode and a lithium metal oxide cathode.

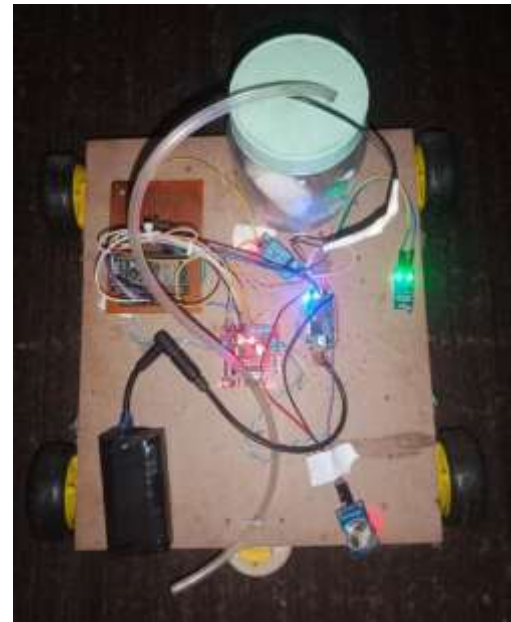
H. DC BO Motor and BO Motor Wheel

A 100RPM DC BO (Battery Operated) motor is a lightweight, low-cost plastic-gear motor designed for DIY robotics, offering a good balance of torque and speed (100 revolutions per minute) at 3V-12V. It drives movement, while the matched BO wheel provides traction and easy attachment to the motor shaft, enabling smooth, reliable motion for small robots.

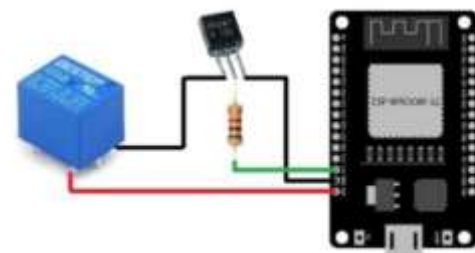
I. Water Motor

A DC water motor functions by converting electrical energy (typically 5V-36V) into mechanical rotational energy, driving an impeller or diaphragm to move, pressurize, or circulate water. It uses magnets to create torque, driving fluids through a pump head using either centrifugal force (high flow) or positive displacement (high pressure).

Hardware Connection



2. Software Implementation



The software architecture of the Solar Panel Cleaner Robot system consists of embedded firmware running on the ESP32-WROOM (38pin) microcontroller and external software applications responsible for AI ML.

Embedded Firmware (Arduino IDE)

The embedded firmware is developed using the Arduino Integrated Development Environment (IDE) and programmed in Embedded C++ AND Python often used together to balance high-performance hardware control with rapid software development.

5.2 IoT Communication and Cloud Upload

The ESP32 connects to the internet through built-in Wi-Fi and uploads sensor readings to the cloud in periodic intervals. This communication makes it possible to observe system status from a remote dashboard and to preserve a record of panel efficiency, cleaning actions, and operating

conditions. The same channel can also be used to receive manual control commands from the user interface.

5.3 AI-Assisted Cleaning Decision

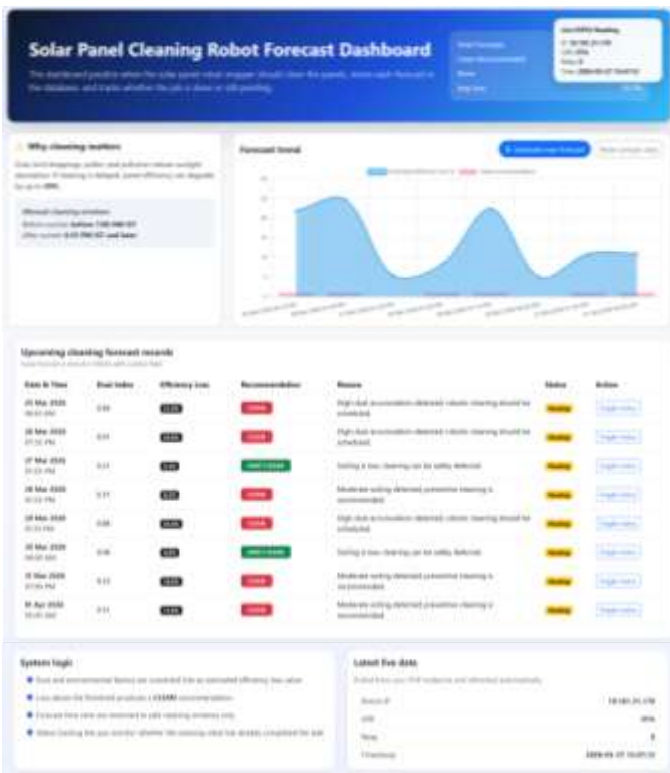
An AI-assisted decision stage analyzes the collected measurements together with historical trends and cleaning history. The purpose of this stage is to identify the point at which dust accumulation begins to degrade the panel output sufficiently to justify cleaning. In this way, the system moves from fixed-time maintenance to condition-based maintenance.

5.4 Cleaning Action and Status Logging

When a cleaning command is issued, the motor system drives the robot and rotates the sponge mechanism while the water pump sprinkles a controlled amount of water onto the panel surface. After the operation, the cleaning status is logged into the history database. The log supports later review of maintenance frequency and system behavior.

5.5 Dashboard and User Interaction

A web-based dashboard provides live data visualization, performance trends, cleaning reminders, and manual override controls. The user or administrator can monitor the panel state, review the historical cleaning record, and issue manual commands whenever required. This interface improves visibility and allows the system to be managed remotely.



VII. OBJECTIVES

- Automated Maintenance: Activating cleaning cycles based on light intensity.
- Environmental Monitoring: Tracking Air Quality Index (AQI) to correlate dust accumulation with local pollution levels.
- Remote Management: Utilizing the ESP32's Wi-Fi capabilities for data logging.
- To develop a web-based monitoring and analytics platform that provides real-time data visualization.
- To implement an AI-based predictive model that analyzes environmental conditions, performance parameters, historical power output data, weather forecasts, dust accumulation trends, and cleaning history to forecast the optimal cleaning schedule.
- To enhance photovoltaic efficiency by ensuring timely and effective removal of surface contaminants (dust, bird droppings, pollen, etc.)

VIII. EXPERIMENTAL RESULT AND PERFORMANCE ANALYSIS



The Solar Panel Cleaner Robot system was experimentally evaluated for real-time monitoring system performance is evaluated against predefined objectives. The effectiveness of AI-based forecasting is measured by comparing predicted cleaning schedules with actual soiling behavior. Based on test results, control parameters, model accuracy, and mechanical efficiency are optimized. This iterative refinement ensures the system delivers maximum efficiency, sustainability, and long-term reliability

IX. APPLICATION

1. **Large-Scale Solar Farms:** Essential for large, remote utility-scale projects where manual cleaning is inefficient, costly, or physically impractical.
2. **Commercial & Industrial Rooftops:** Provides a safe, automated solution for cleaning vast arrays on warehouses or office buildings, reducing human operator risk in high-voltage areas.
3. **Residential Solar Systems:** Allows homeowners to maintain peak efficiency without climbing on roofs, using compact, portable, and often, waterless robotic cleaners.
4. **Arid and Dusty Regions:** Ideal for areas prone to high dust accumulation, where robots frequently clean to prevent significant drops in power generation.
5. **Agricultural Settings:** Removes dirt, farming debris, and bird droppings from solar panels powering irrigation systems or greenhouses.
6. **Urban Infrastructure:** Cleans public solar-powered systems like street lights and traffic signals to maintain energy efficiency in high-pollution areas.

X. FUTURE SCOPE

1. **Autonomous AI Navigation:** Future robots will utilize AI-driven path planning, machine learning, and LiDAR for high-resolution 3D mapping and 360-degree navigation in complex environments.
2. **Water-Free and Eco-Friendly Tech:** To address water scarcity, robots will favor dry-cleaning mechanisms, such as electrostatic or microfiber brushes.
3. **Self-Sustaining Operations:** Integration of PV panels on the robots themselves to allow them to recharge directly from the solar panels they are cleaning.
4. **Advanced Drone Integration:** UAV (Drone) systems will be used for deploying, inspecting, and retrieving robots across large, remote solar sites.
5. **Versatile Design:** Enhanced adaptability to clean angled, elevated, and even vertical installations.

XI. CONCLUSION

This paper presents an integrated IoT-based solar panel cleaning robot with an AI-assisted cleaning decision layer and a web-enabled reminder system. The architecture unifies sensing, communication, actuation, and monitoring into a single workflow.

By combining an ESP32 controller, a motor-driven cleaning mechanism, cloud connectivity, and condition-based maintenance, the proposed system offers a practical route toward maintaining solar panel efficiency with less manual intervention.

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